

Inherent Relation between Nernst Signal and Nodal Quasiparticle Transport in Pseudogap Region of Underdoped High Temperature Superconductors

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In-plane Nernst signal and resistivity have been measured for three $La_{2-x}Sr_xCuO_4$ single crystals ($x=0.09, 0.11$ and 0.145) with the magnetic field parallel to c-axis. A quadratic temperature dependence of resistivity, i.e., $\rho = \rho_0 + aT^2$ is observed below a certain temperature T_R . It is found that the upper boundary of the Nernst signal T_n coincides with T_R , which points to an inherent relation between the anomalous Nernst signal and the nodal quasiparticle transport in the pseudogap region. Finally a phase diagram together with the pseudogap temperature T^* is presented, which suggests a second energy scale in the pseudogap region.

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One of the core issues in high temperature superconductors is the origin of a pseudogap above T_c in underdoped region. In order to understand the physics behind the pseudogap, many models have been proposed, such as resonating valence bond (RVB)[1] theory, spin fluctuation[2], preformed Cooper pairs[3], charge stripes[4], d-density wave (DDW)[5, 6], etc. Among many of them, the pseudogap state has been considered as a precursor to the superconducting state. In this precursor state, Cooper pairs have already formed before the long range phase coherence (or Bose-Einstein like condensation) is established. Measurements on the high frequency complex conductivity illustrate that a short-life phase coherence can persist up to about 30 K above T_c and these data can be described by the dynamics of thermally generated topological defects (free vortices)[7]. The Princeton group found that a significant in-plane Nernst signal[8] appears in the pseudogap region with $H \parallel c$. This may be understood by the phase-slip due to the thermal drifting of vortex-like excitations. However, it remains unknown how does this strong Nernst signal relate to the nodal quasiparticles which are supposed to dominate the in-plane transport properties in low temperature region. In this Letter we present the evidence for an inherent relation between the Nernst signal and nodal quasiparticle transport: The upper boundary temperature T_n of Nernst signal is found to coincide very well with a crossover temperature T_R below which a quadratic temperature dependence of resistivity is observed. Possible reasons are given to explain this coincidence.

The single crystals measured in this work were prepared by travelling solvent floating-zone technique. Samples with three different doping concentrations $p=0.09$ ($T_c=24.4K$, as grown, $x=0.09$), 0.11 ($T_c=29.3K$, as grown, $x=0.11$), 0.145 ($T_c=36.1K$, nominal $x=0.15$) have been investigated. The quality of our samples has been characterized by x-ray diffraction, and $R(T)$ data showing a narrow transition $\Delta T_c \leq 2 K$. For some samples, the full width at the half maximum (FWHM) of the rocking

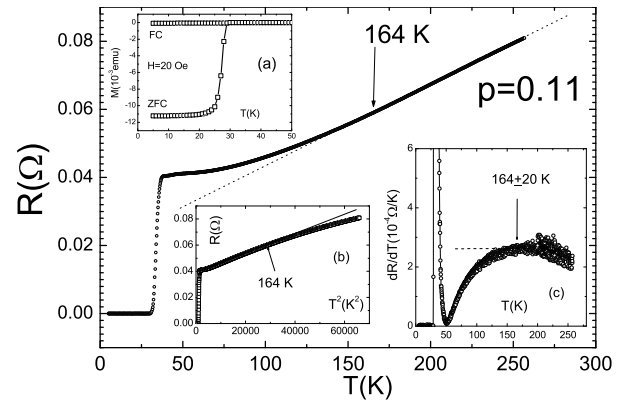


FIG. 1: Temperature dependence of resistivity for sample $p = 0.11$ (shown here as a typical example). An enhancement of resistivity is observed below a temperature T_R (here about 164 K). Below $T_R=164 \pm 20 K$ a quadratic temperature dependence of resistivity has been observed (see the linear part of Fig.1(b)). In Fig.1(c) we show the derivative of resistivity versus T . It is clear that the derivative dR/dT starts to drop down at about 164 K. Similar behavior is found for other two samples with $p = 0.09$ and $p = 0.145$ although the T_R are different.

curve of (008) peak is only 0.10° [9]. The samples have also been checked by AC and DC magnetization and resistive measurements. Inset(a) of Fig.1 shows a typical curve of the diamagnetic transition of sample $p = 0.11$ measured at $H = 20 Oe$.

The resistivity was measured by using standard four-point technique. For measuring the Nernst effect we adopted the one-heater-two-thermometer technique. A heating power of 2 mW is applied to one end of the single crystal and two tiny thermometers with distance of 1.5 mm are attached to the sample for measuring the temperatures along the heat flow (longitudinal) direction. The Nernst voltage is measured through two contacts on two opposite planes at the symmetric positions. Very small contacting resistance ($\leq 0.1 \Omega$) has been achieved

by using silver paste. All samples are shaped into a bar structure with dimensions of $4 - 5\text{ mm}$ (length) $\times 1\text{ mm}$ (width) $\times 0.5\text{ mm}$ (thickness). All measurements are based on an Oxford cryogenic system (Maglab-12) with temperature fluctuation less than $0.04\%T$ and magnetic fields up to 12 T. During the measurement for Nernst signal the magnetic field is applied parallel to c - axis and swept between 7 to -7 T and the Nernst signal V_N is obtained by subtracting the positive field value with the negative one in order to remove the Faraday signal during sweeping the field and the possible thermal electric power due to asymmetric contacts. The Nernst voltage is measured by a Keithley 182-Nanovoltmeter with a resolution of about 5 nV in present case. In this paper we show the Nernst signal $e_y = E_N/|\nabla T|$, where $E_N = V_N/d$ with d the distance between the two contacts for Nernst voltage, ∇T is the temperature gradient along the heat flow direction.

Fig.1 shows the temperature dependence of resistivity for sample $p = 0.11$ (as a typical example). One can see that a quasi-linear behavior is observed above a characteristic temperature T_R at about 164K. It is necessary to note that this quasi-linear part (as marked by the dotted line) is different from the linear part above T^* which is about 400K for $p = 0.11$. Below T_R the resistivity deviates from the linear behavior. In Fig.1(b) we present ρ vs. T^2 . One can see that below about $164 \pm 20\text{ K}$, the curve possesses a linear behavior which indicates a relation of $\rho = \rho_0 + aT^2$. In order to determine T_R with higher accuracy, we present in Fig.1(c) the derivative of resistivity $d\rho/dT$ vs. T , it is evident that at about $T_R = 164 \pm 20\text{ K}$ the derivative starts to drop down showing a crossover from a quasi-linear behavior (above T_R) to a quadratic behavior below T_R . Similar features are observed for other two samples ($p = 0.09$ and $p = 0.145$). Note that Ando et al.[10] recently reported that the relation $\rho = \rho_0 + aT^2$ in low temperature region for underdoped La-214 and Y-123 systems, and proposed that this behavior is characteristic of the nodal quasiparticles on the so-called Fermi arcs. It is found also by these authors that T_R increases towards more underdoping.

Fig.2 presents the Nernst signal of sample $p = 0.11$ with thermal stream along [110] direction (the sample was cut with the longitudinal direction along [110]) and at temperatures from 5K to 220K. In order to show the reliability of the measurement, we repeated the measurements at 20, 25 and 220K after a 2-day delay. One can see that the two sets of data for each temperature coincide very well showing a high reproducibility. In low temperature region, the Nernst signal is dominated by the motion of Abrikosov vortices. One can easily see that the background when the vortices are frozen (see data at $T = 5, 10, 15\text{ K}$ in low field region) is actually precisely zero. This is contrasted by the slight negative background at high temperatures (above 150K). As first discovered by the Princeton group[8] and later checked

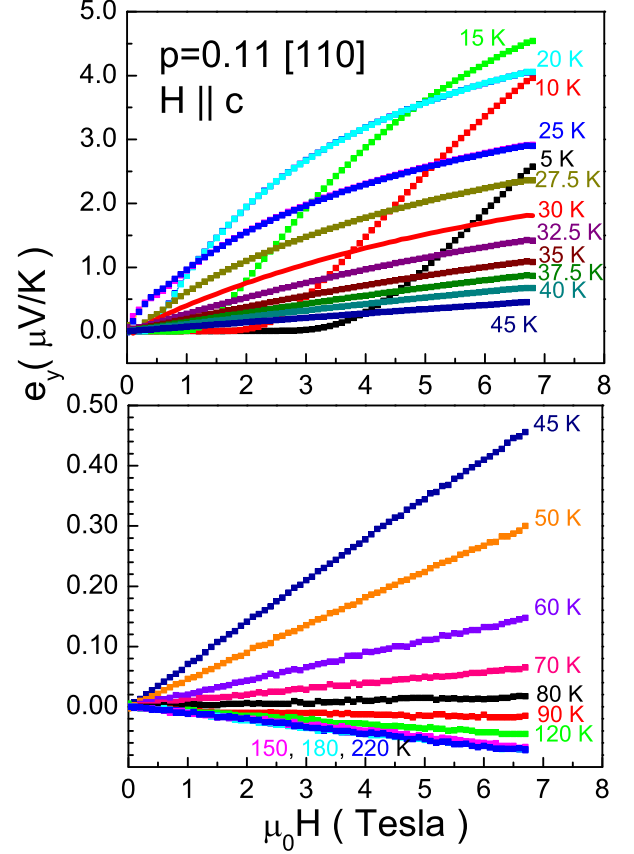


FIG. 2: Nernst signal of sample $p = 0.11$ at temperatures from (a) 5 K to 45 K and (b) 45 K to 220 K. The measurement at 20, 25 and 220 K were repeated and data overlap each other for each temperatures. At temperatures of 5 K, 10 K, 15 K, the vortices are frozen showing a background with precisely zero resistivity. At temperatures above about 150 K all data overlap to a background with a negative slope.

by us[11], a strong in-plane Nernst signal can be measurable far above T_c (here $T_c = 29.3\text{ K}$ for $p = 0.11$). Here it shows the same case. When T is above 80K, the signal becomes negative and gradually it approaches a background with a negative slope. And when T is above about 150K the Nernst signal does not change anymore with T , therefore it is reasonable to define an upper boundary T_n for the Nernst signal which locates in the region of 150 – 180K for sample $p = 0.11$ with thermal flow direction along [110].

In Fig.3 the Nernst signal from both samples ($p = 0.11$ along [110] and [100]) at 6 T is shown vs. T . The red (solid) curve is an empirical relation $\Delta e_N = e_N^0/T^{3.3}$ which describes the data very well up to about 120K and a deviation from this behavior with a faster dropping rate occurs above about 120K. It is thus safe to conclude that the Nernst signal vanishes in the region of 150K to 180K as marked by a rectangle in Fig.3(b). Surprisingly this upper boundary temperature T_n of Nernst signal coincides rather well with the crossover temper-

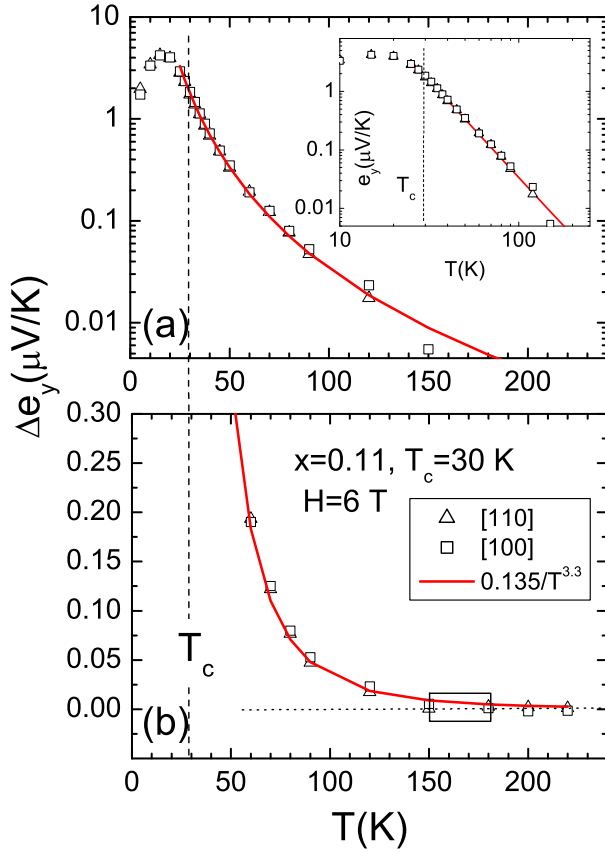


FIG. 3: Net Nernst signal Δe_y (subtracted with the background at 220 K) at 6 T shown in (a) semi-logarithmic and (b) linear scale for samples ($p = 0.11$) with thermal stream along [110] (open triangle) and [100] (open square). From both figures one can see that the Nernst signal vanishes in the region of 150 K to 180 K as marked by a rectangle in Fig.3(b). The solid line shows an empirical relation $\Delta e_y = 0.135/T^{3.3}$ which describes the data above T_c very well but the reason remains unknown. Inset of Fig.3(a) shows the same data in double logarithmic scale.

ature $T_R = 164 \pm 20$ K as mentioned above. For sample ($p = 0.11$) we have measured on two specimens, one with the heat stream along [100] and another one along [110]. The results on these two samples turn out to be almost identical (as shown by open squares and triangles in Fig.3). Then we checked for other two samples with doping $p=0.09, 0.145$ and found that this coincidence of T_R and T_n is true also for them. From the recent published data of Ando et al.[10] the T_R has also been determined and shown together with our data in Fig.4. It is clear that the data from both groups overlap each other. In Fig.4 we also present the doping dependence of T_n given by the Princeton group. In the very underdoped region, according to Ando et al.[10], the crossover of resistivity occurs at higher temperatures. For example, at $p = 0.02$, T_R is about 230 K. However the upper boundary of Nernst signal is obscured by both the small Nernst

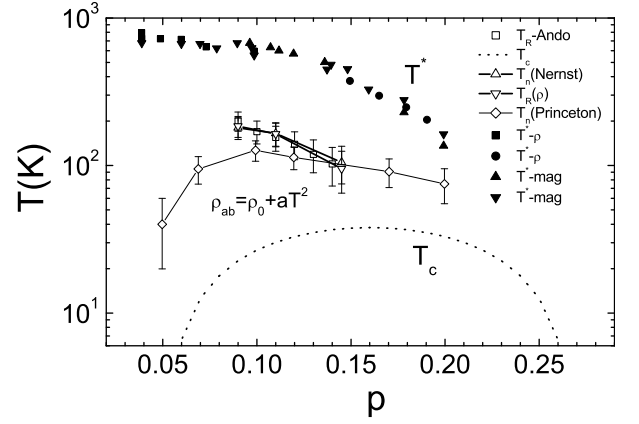


FIG. 4: Phase diagram of $La_{2-x}Sr_xCuO_4$ single crystals. The bottom dotted line represents an empirical curve of $T_c/38 = 1 - 82.6(p - 0.16)^2$. The filled symbols represent the temperatures T^* (quoted from [13]) below which the Fermi surface is partially gapped. The $T^* - \rho$ was determined from the resistivity and $T^* - \text{mag}$ was determined as the point where the Knight shift starts to decrease. The open symbols are determined from our measurement for T_n and T_R , T_R from Ando et al.[10] and T_n from Wang et al.[12]. The upper boundary of Nernst signal (T_n) and the crossover temperature of resistivity T_R coincide rather well in the doping regime of our present samples.

signal and strong thermal power in very underdoped region. Therefore we don't know whether this coincidence holds still for very underdoped samples. If taking a fixed value which is determined by the resolution of the voltmeter as a criterion for the Nernst signal, according to the recent data of the Princeton group[12], the Nernst upper boundary temperature T_n will drop down in very underdoped region. Despite the uncertainty in determining the value of T_n , in the doping region of our samples ($p = 0.09, 0.11, 0.145$), the data are not far from that of the Princeton group.

In the following we will try to understand the coincidence of T_n and T_R in the intermediate doping region based on several possible pictures. We first discuss the scenario of vortices. It is known that the in-plane resistivity normally reflects the dynamics of the nodal quasiparticles, while the Nernst signal is induced by the thermal drifting of vortices as suggested by the Princeton group, therefore it seems difficult to relate one and another. However one way to understand this point is that the nodal quasiparticles partially form Cooper pairs and induce a precursor superconducting state which has strong phase fluctuation with vortices as one of the important excitations. Therefore below this specific temperature the Nernst signal which senses the vortex motion starts to appear and the temperature dependence of resistivity changes behavior (due to probably the reduction of the effective charge carriers). As a partial support to this picture, it was shown that this strong in-plane Nernst

signal may be explained by the superconducting fluctuation which has the Kosterlitz-Thouless vortex-anti-vortex pairs as the topological excitations[14]. The second picture close to this vortex scenario is based on the bosonic RVB[15] which predicts the co-existence of spinon vortices and quasiparticles below T_n and the Nernst signal is induced by the motion of these spinon vortices. This picture naturally predicts a second energy scale (T_n or T_R) and different type of vortices below and above T_c (still lacking of experimental evidence for the spinon vortices). However both pictures are facing a common difficulty: No any trace of vortex (or spinon vortex) flow resistivity has been reported far above T_c . One explanation to this point would be that the resistivity induced by quasiparticle scattering is overwhelmingly larger than the flux flow resistivity. Meanwhile it remains to be understood why the temperature dependence of resistivity should be precisely quadratic. Two close relatives of the picture based on vortices are the one with a mixture of composite charge carriers[16, 17] or the pair density wave (PDW)[18] (co-existence of Cooper pairs and free electrons below T_n). The paired electrons tend to localize and the rest free electrons contribute to the electrical conductivity. According to Ando et al.[10], the relation $\rho = \rho_0 + aT^2$ may not be simply due to the scattering rate $1/\tau \propto T^2$ of the nodal quasiparticles since the effective charge carrier density changes with temperature even below T_R . A naive explanation for $\rho = \rho_0 + aT^2$ in this region would be that the nodal quasiparticle density (roughly proportional to the length of Fermi arc[19] or the electronic specific heat coefficient γ [20]) drops down linearly with T , but the scattering rate $1/\tau$ of nodal quasiparticles with features close to Dirac fermions is proportional to T^3 . One more possibility for the coincidence of T_R and T_n relies on an exotic picture that some kind of unconventional charge density wave (UCDW)[21] occurs at T_n . Below T_n or T_R the quasiparticle spectrum on top of this UCDW will contribute a strong Nernst signal, while the nodal quasiparticles are responsible for the in-plane resistivity, thus both the in-plane Nernst signal and resistivity will certainly correlate each other. This picture needs both theoretical justification and experimental evidence, especially a recent calculation seems ruling out the D-density wave as one of the possible causes[22]. Since the Nernst signal is detectable only below T_R , it may have no direct relation with the "flat band" near $(\pi, 0)$ as observed by ARPES since it influences the transport properties only at high temperatures[23]. The coincidence of T_R and T_n found in our experiment strongly suggests an inherent relation between the Nernst signal and the nodal quasiparticle transport. This may also imply a second energy scale in the pseudogap region.

In conclusion, the in-plane Nernst signal and a quadratic temperature dependence of resistivity are found to occur in the same temperature region above T_c

in the intermediate underdoped regime. This suggests a close and inherent relation between Nernst signal and the nodal quasiparticle transport. Possible reasons are given to explain this coincidence. This coincidence may be obscured by other effects in other doping regimes. Our observation may imply a second energy scale or temperature within the pseudogap region.

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